DOCUMENT RESUME

ED 341 480 PS 020 254

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TITLE A Computer Simulation Model of Acquisition of Transitive Inference.
PUB DATE Apr 91
NOTE 23p.; Paper presented at the Biennial Meeting of the Society for Research in Child Development (Seattle, WA, April 18-20, 1991).
PUB TYPE Reports - Descriptive (141) -- Speeches/Conference Papers (150)

EDRS PRICE MF01/PC01 Plus Postage.
DESCRIPTORS *Children; *Cognitive Development; *Computer Simulation; Computer Software; Foreign Countries; *Serial Ordering; *Thinking Skills
IDENTIFIERS *Computer Models; Ordering Operations; *Transitive Inferences

ABSTRACT

This paper describes a computer model that simulates the way children develop the reasoning skills of transitive inference and the construction of ordered sets. The computer model begins from general operations, such as setting and removing goals, storing and retrieving information, comparing elements to find matches, reading premises, and giving feedback. The program sometimes produces errors due to processing and memory storage difficulties. The model implies that the development of reasoning involves the development of strategies, and that strategies are built on general and specific knowledge acquired through everyday experience. A list of 14 references is included. (BC)

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A Computer Simulation Model of Acquisition of Transitive Inference

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Paper presented to Biennial Meeting of the Society for Research in Child Development, Seattle, Washington, April 18-20, 1991.

This project was designed to model the way children develop basic reasoning skills by practise within a domain, using their world knowledge. Transitivity, and the closely related task of constructing ordered sets, were chosen as the focus of the study because they are developmentally important landmarks, there is a large, high quality data base, and they are important to practical skills such as ordering and quantification.

An example of a transitive inference is shown in Figure 1.

SHOW TRANSPARENCY 1 HERE

The premises are

John is happier than Bill
Tom is happier than John

The process of making a transitive inference entails integrating the premises into a single ordered set, Tom, John, Bill. The inference, Tom is happier than Bill is then easily made from the ordered set. The research of Riley and Trabasso (1975), as well as Sternberg's (1980) model, both indicate that integrating premise representations into an ordered set is a key component of transitive inference. Furthermore, as Thayer & Collyer (1978) have pointed out, once the ordered set is constructed, making the inference is almost perceptual. Therefore ability to construct the ordered set is at the core of our model.
The model begins with domain-general strategies, and develops the strategies it needs for a particular domain through experience with that domain. The development of the strategies is constrained by the concept of the task. In this respect the model resembles that of Greeno, Riley and Gelman (1984), which showed how counting strategies were constrained by a concept of number. In our model strategy development is constrained by a concept of order. It is therefore inherent in the model that acquisition of transitive inference strategies is based on an understanding of the task, as

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represented in the concept of an ordered set which a child is postulated to have. However not all strategy development is based explicitly on understanding, and associative strategy development mechanisms are incorporated through the strengthening and weakening of strategies according to their success.
The properties of a psychologically realistic concept of order are shown in Figure 2.

SHOW TRANSPARENCY 2 HERE

It is assumed that the participant must know:
1 at least one relation, such as greater than, happier than etc.,
2. that each element occurs once and only once
3. that end elements have the same relation to all other elements; e.g. in an ordered set {a,b,c,d}, a has the same relation to all of b,c,d.
4. the position of an element which is not at the end is defined by its relation to elements on each side of it; e.g. b<a, b>c.
5. the same relation exists between all pairs (this effectively provides the transitivity property of the concept of an ordered set).

All these properties can be instantiated in any ordered set of at least three elements. This has important implications, because it means that a child who knows an ordered set of at least three elements has a basis for a concept of order. Furthermore a concrete instance of an ordered set can be used by analogical reasoning.

Children encounter plenty of concrete instances of ordered sets. Children of different sizes can form an ordered set, as also can stackable blocks or other toys that vary in size. The three bears also form a nice ordered set of three elements; daddy, mummy, baby bear are ordered for size and a number of other attributes. Therefore children have plenty of experiences which provide them with the basis for a concept of order.

A concrete example of an ordered set can be used by analogy to constrain the solution to a transitive inference problem. Consider for example a child who had no strategy for the transitive inference task; John is happier than Bill, Tom is happier than John, who is happiest? A concrete instance of an ordered set, such as three different-sized blocks, can be used as an analog, as shown in Figure 3.

SHOW TRANSPARENCY 3 HERE

Tom is mapped into the largest block, John into the middle block, and Bill into the smallest. The relation "happier than" then

consistently corresponds to "larger than". By contrast, an incorrect ordering would be inconsistent, as shown in Figure 4.

SHOW TRANSPARENCY 4 HERE

In this case, "larger than" corresponds to "happier than" on two occasions, and to "sadder than" on the third occasion. The mapping of problem into concept of order or, in terms of Gentner's (1983) theory, of target into base, is inconsistent, and therefore invalid according to the definitions of structure mappings provided by Halford (1987) and Holyoak and Thagard (1989).

A specific case of an ordered set can therefore provide a kind of "template" for the correct ordering of the elements in a transitive inference task, through analogical reasoning. For participants who have no transitive inference strategies, a concrete analog can be used as a criterion for the development of strategies. Once the strategies exist, there is no longer any need for analogical reasoning.

Notice that, in order to detect that the mapping is inconsistent, and that the ordering is incorrect, both premises must be processed jointly. If we consider only one half of the diagram, the inconsistency is not apparent. Similarly, the correct ordering of the premise elements requires both premises to be processed jointly. If we consider only John is happier than Bill, we can allocate John to the first or second position, but cannot determine a unique ordinal position for either element. Both premises must be processed to allocate any or all elements to unique ordinal positions. This has been shown to impose a high processing load (Maybery, Bain, & Halford, 1986; Halford, Maybery & Bain, 1986). It implies that reference to the concept of order to determine the correct ordering will also impose a high processing load. Ability to process this load is one of the parameters which vary with age.

Play experience with concrete instances of ordered sets provides children with the declarative knowledge they require to guide their development of transitive inference strategies. However they also need procedural knowledge. This is mainly in the form of operators, together with their initial and final states. An example of an operator that is useful in constructing ordered sets is APPEND, which is illustrated in Figure 5.

SHOW TRANSPARENCY 5 HERE

For example, given that elements ab are already in order, when the premise b>c is presented, it is useful to append c onto ab, yielding

abc. Physical actions, or the motor equivalent of the append operator, can be learned by play experiences. That is, children can learn that if you have a row of elements, you can add another element to the row, so it becomes the end element. Such actions form the building blocks of strategies for ordering objects. In our model they are assumed to have been learned and stored in memory, and be available for use by means-end-analysis. That is, if the initial state, and the desired final state are known, an appropriate operator can be selected by searching memory.

The model is implemented as a self-modifying production system written in PRISM II (Ohlsson & Langley, 1986). When it begins to run it has only domain-general productions which perform such actions as setting and removing goals, storing and retrieving information, comparing elements to find matches, reading premises and giving feedback. It builds productions specific to transitive inference through experience with the task. We will give an example using a sample problem as shown in Figure 6. Once built, the productions construct an ordered set in working memory, consistent with the mechanisms demonstrated by Foos, Smith, Sabol & Mynatt (1976).

SHOW TRANSPARENCY 6 HERE

The first premise is a>b. The model checks whether there is an ordered string already in working memory, finds there is not, and adds the string ab to working memory. This can be done because the model is set up with domain-general productions for storing information in working memory. When the premise b>c is presented there is no production that has a string in working memory plus a premise, in its condition side, because the model is not equipped initially with productions for dealing with transitive inference.

This puts the model into a modification phase. First it searches for a concept appropriate to its present goal, which is ORDER OBJECTS. This causes the concept of order to be retrieved from memory. Analogical reasoning is used to determine the correct order, by mapping the premises a>b and b>c into an ordered set retrieved from memory, as shown in Figure 7

SHOW TRANSPARENCY 7 HERE

It is recognized that the ordering abc would be consistent with the concept of order. Means-end analysis is then used to select an operator which will produce the order abc. Then a new production is built which includes the APPEND operator, as shown in Figure 8.

SHOW TRANSPARENCY 8 HERE

This production will match any state in which working memory contains one or more objects in a string, and the first object in the premise matches the last object in the string. On the action side, the APPEND operator will place the second object in the premise on the end of the string.

When a subsequent problem occurs which requires this production it will fire, without the effortful process of having to build it. Thus strategies, which in this model consist of productions, can operate in relatively automatic fashion once they are acquired. Understanding is not required for problems of a type which the model has already learned to solve.

When a correct solution is obtained, positive feedback increases the strength of the productions involved in the solution. Negative feedback results in weakened productions. Productions that lead to errors are gradually weakened below threshold, and cease to fire. This clears the way for construction of new productions that avoid the errors.

When the model first builds productions, some of them do lead to errors. One type of error is due to a processing deficit, which produces a tendency to focus on the most recent premise, ignoring the implications of earlier premises. We call this the relational strategy, and it is illustrated in Figure 9, using a problem form studied by Foos et al. (1976) and in our own laboratory.

SHOW TRANSPARENCY 9 HERE

The first premise, c>d results in the string cd being stored in working memory. The next premise, a>b contains no element which matches any element in cd. If the model is operating at a low level of cognitive effort, either because of low arousal or because of competition for resources, then it pays attention only to the most recent premise. Ability to allocate sufficient resources to process two premises jointly is a parameter which increases with age. Therefore

the production that is built simply inserts ab after cd, yielding the order cdab, without recognizing that the order of the pairs is indeterminate. When b>c is presented, attention is again paid only to the most recent premise, resulting in a production which simply switches b to the front of the list, yielding the order bcda. Data from Foos et al.'s (1976) study, and from our own laboratory, show this is a common error for children, and for adults under high processing load.

This error leads to negative feedback, which weakens the productions involved in the incorrect solution, clearing the way for new productions to be built. The negative feedback also increases effort, which causes the most recent premise to be integrated with previous premises when a new production is being built. This leads to a production based on what we call the system strategy, which is shown in the lower half of Figure 9.

SHOW TRANSPARENCY 9 AGAIN HERE

Now when a>b is appended to the string, a marker is inserted to indicate that the order of the pairs is indeterminate. Then when b>c is presented, a production is built that switches ab to the front of the string, yielding abcd. Correct feedback strengthens this production.

The model makes these errors when it first builds strategies, but then builds new productions which provide correct solutions to problems with all permutations of premises. It also recognizes when a problem is unsolvable, because it codes indeterminacies in the ordered set in working memory.

Errors can result from both processing and memory storage difficulties. The first has the consequence illustrated above. It occurs because mapping two premises into an ordered set imposes a high processing load, as some of our previous research has demonstrated (Halford et al., 1986; Maybery et al., 1986). Furthermore young children have particular difficulty considering two premises jointly , even when short term retention problems are eliminated by memory aids.(Halford, 1984; Halford & Kelly, 1984). There is therefore a processing deficit because the load imposed by two premises causes children, and to a lesser extent adults, to consider only the most recent premise in default, which causes the kinds of errors we have seen.

The second source of errors is forgetting part of the string. The most common error is to lose the indeterminacy marker, as Foos et

al. (1976) have shown. Thus even adults, who have already developed appropriate strategies, make errors sometimes due to excessive short term memory load. Children are more prone to lose information from short term memory in this way, and this is another parameter which varies with age.

SHOW TRANSPARENCY 10 HERE

CONCLUSIONS

1. The model begins with domain-general knowledge and, by building productions, it develops its own strategies for a specific domain, in this case transitive inference and ordering tasks.
2. Previous, concrete experience is used to guide the development of strategies, by analogical reasoning. The concept of order is based on knowledge that any child could be expected to acquire.
3. Procedural knowledge is utilized by means-end analysis.
4. The model blends metacognitive strategy development processes, based on understanding of the concept of order, with associative strategy development mechanisms, based on strengthening and weakening of productions. However understanding is not required for routine application of strategies.
5. The model reproduces the most common errors on a selection of problem forms which includes all permutations of premises.
6. The model recognizes indeterminate problems in a way that follows naturally from its understanding of the concept of order.
7. The model corrects its own errors by building more adequate strategies.
8. The model provides a "sufficiency test" for a theory which holds that reasoning skills can be acquired by an active construction process that works on knowledge gained in everyday experience.
9. The acquisition process utilizes principles and processes that have been validated in other contexts (including the work on cognitive skills based on Anderson's ACT* theory). The same principles apply to children and adults, which differ only in a number of efficiency parameters.
10. The model implies that strategies are part of what develops, but these strategies are built on domain-general and domain-specific knowledge acquired through everyday experience. Furthermore the

construction of strategies is modulated by information processing and memory storage parameters.

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John is happier than Bill

Tom is happier than John

Constructed order (in STM)

Tom John Bill

inference

Tom is happier than Bill

CONCEPT OF ORDER

1. asymmetric binary relations

   (greater than, happier than)

2. each element occurs once

3. end elements have the same relation to all other elements

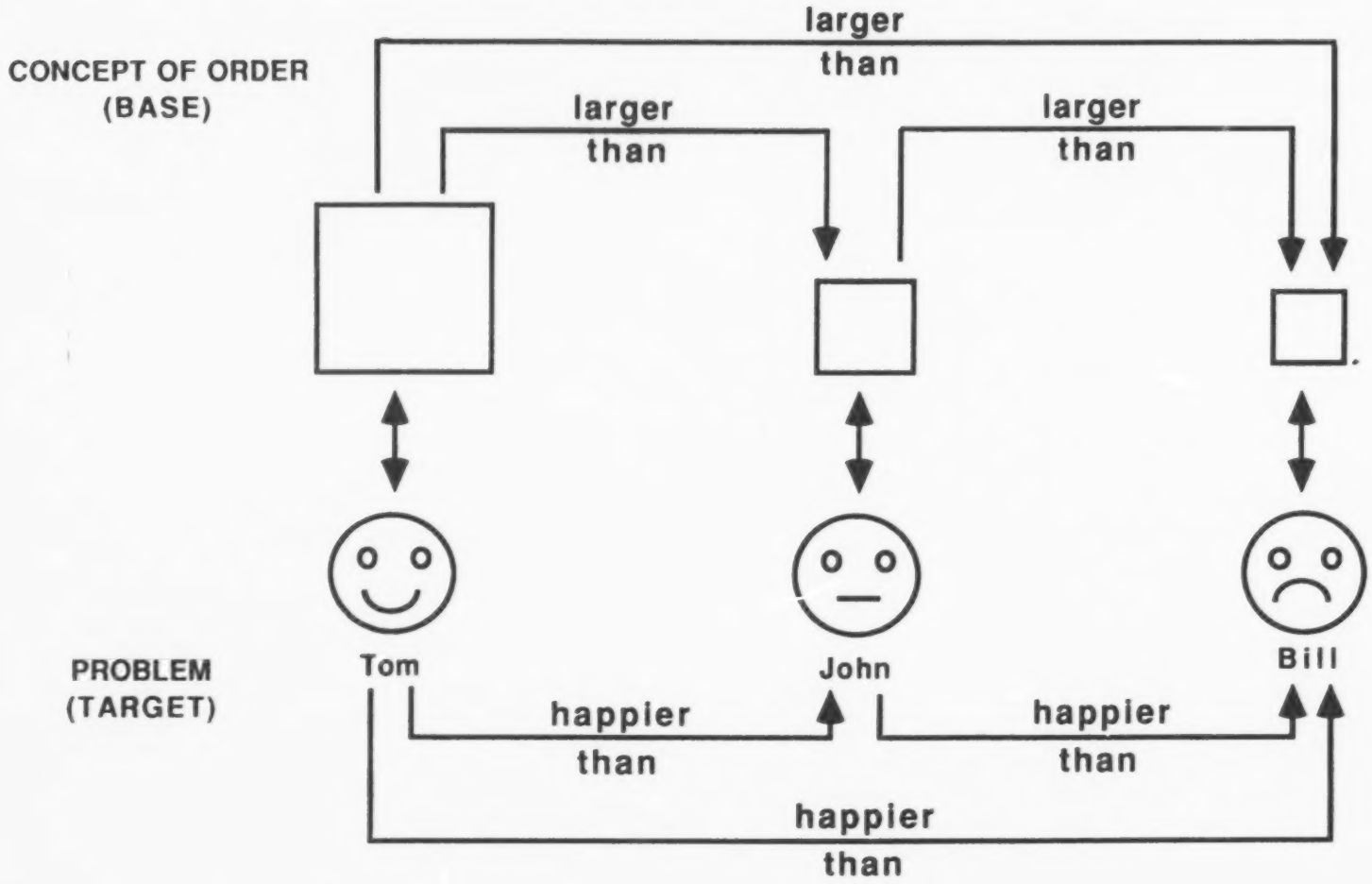
   (a > b > c > d)

4. position is defined by relation to neighbors

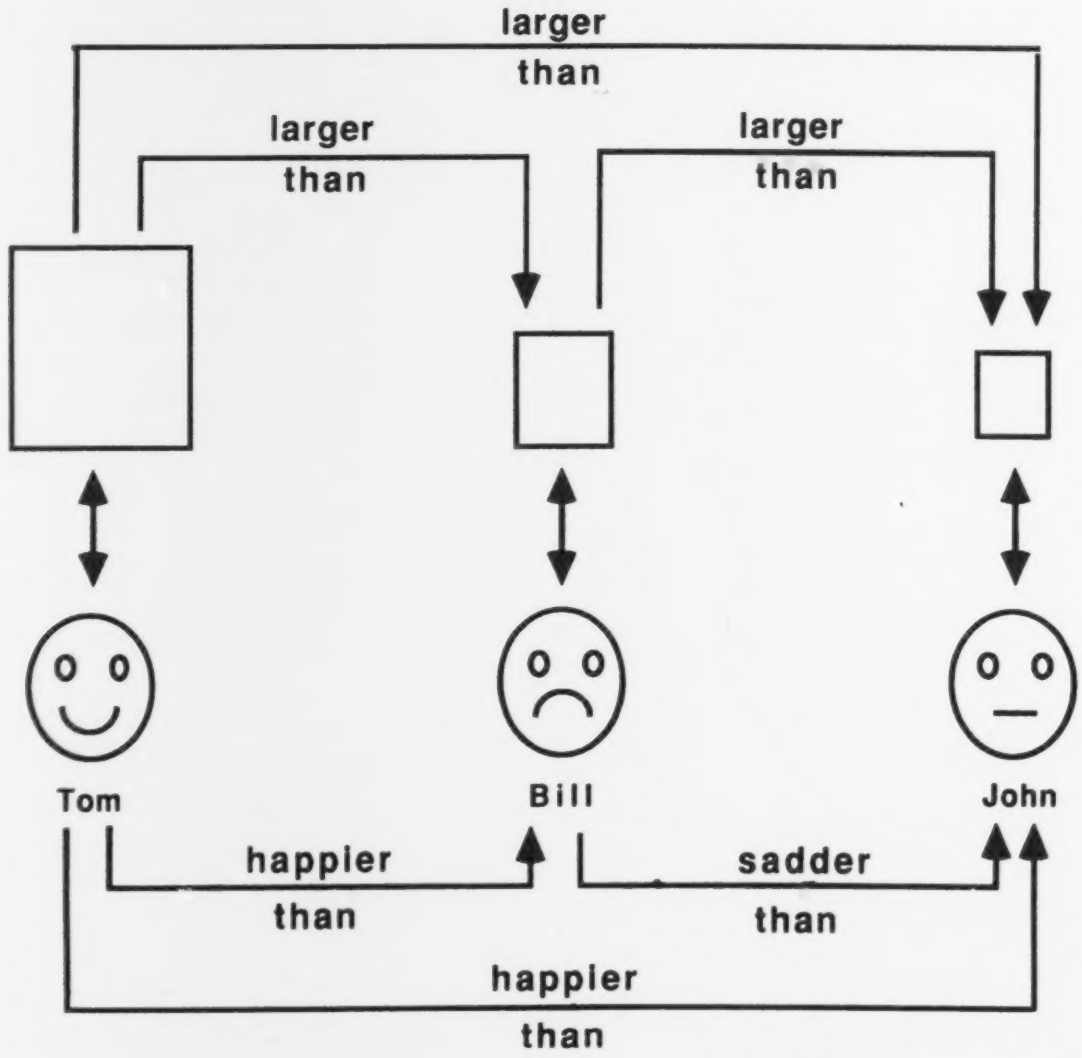
   (b < a, b > c)

5. all pairs have the same relation

   (a > b, b > c, a > c)

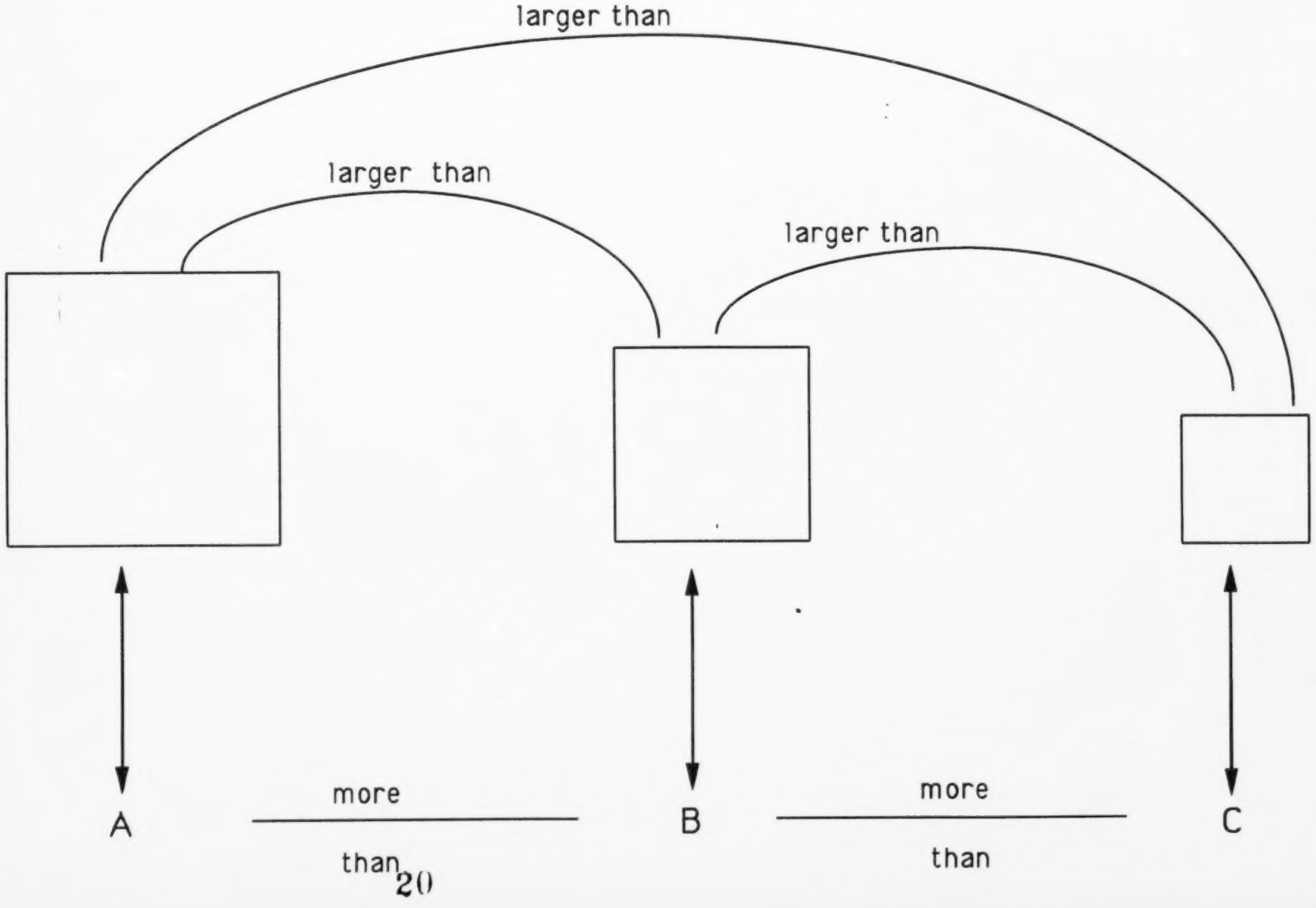

CONCEPT OF ORDER
(BASE)
larger
than
larger
than
larger
than
PROBLEM
(TARGET)
Tom
John
Bill
happier
than
happier
than
happier
than

CONCEPT OF ORDER
(BASE)



Constructed Order	Premise	Action
a b	b > c	append
a b c		

Constructed Order	Premise	Action
- - -	a > b	insert in WM
a b	b > c	append
a b c		


larger than
larger than
larger than
A
more
than
B
more
than
C

Production built:

(((constructed order (<relation> <obj a> . . . . . obj n>))

(new premise <obj 1> <relation> <obj 2>)

(match obj 1 obj n))

(add-to WM (perform APPEND <obj n> <obj 2>)))

Instantiation:

working-memory contents	premise	new working-memory contents
ab	b>c	abc

	constructed order	premise	action
	- - -	c > d	insert in WM
Relational Strategy	c d	a > b	concatenate
	c d a b	b >c	delete - insert
	b c d a		
	- - -	c d	insert in WM
	c d	a > b	concat indet
System Strategy	(cd)^(ab) *	b > c	switch
	a b c d		

* indeterminacy marker